9. Invisible Light

typos fixed 1 Nov 2005

An opening anecdote:

Watching illegal immigrants cross the border

In 1989, I had an opportunity to spend a night with the US border patrol that guards the US/Mexican border near San Ysidro. After touring their facilities, and having dinner, we went to a hillside overlooking the border just as the sun was setting. Many people were gathering on the Mexican side. There were stands selling them tacos and hot dogs, primarily (I was told) to people who had been caught the night before, and had to spend a day waiting until nightfall to try again.

It began to get dark, and the other side of the border was getting crowded. I could still see everyone clearly. Suddenly one boy ran to the fence, climbed over, and ran to hide on the US side. That seemed to trigger an avalanche. Hundreds of people swarmed towards the fence, young and old, some with ladders, and in a few minutes they were all across and disappearing into the gullies of the desert on the United States side.

Our hosts, the border patrol, did nothing for a while, and then drove us along a dirt road up to a hilltop. By the time we got there, it was dark. The lights of Tijuana twinkled in the distance, but the desert between us and the border was dark. On the back of a jeep, the border patrol mounted a special pair of binoculars, and they were surveying the darkness. The binoculars were cooled with liquid nitrogen, and hooked to a battery. These were "night vision" binoculars. I was allowed to use them myself, and scan the countryside. Through the binoculars, I could see mostly blackness, the outline of the hills, and in the valleys (from our high vantage point), clusters of people glowing in the dark. Their faces and hands were bright, and the rest of their bodies somewhat dimmer. They were waiting. At one location they had lit a small fire (visible even with the unaided eye as a small reddish spot) and that was extremely intense white in the binoculars.

What are they waiting for?' I asked.

"Their guides," the Border Patrolman replied. The immigrants had been given simple maps to show them how to get away from the border, to a location that they could find less than a mile in from the border. This is where they would be met by the guide whom they had hired.

"They waited a long time, and so did we. Finally, after over an hour, the groups started moving through the gullies. I wondered if they knew how easily we could see them in the absolute darkness. As one group approached a road, we drove over to them. They heard the car coming, and waited. I asked, why don't they run? The answer: because it's too dangerous, they might get lost, and besides, if they do get caught, we will only send them back to Mexico, and then they can try again tomorrow."

Richard A. Muller, 1999

For a non-physics observation on these events, see the footnote[1]

What were the mysterious binoculars? How could they see in the dark? Where was the illumination coming from? Why did they require liquid nitrogen?

The image below shows a photograph taken with invisible light of men climbing (and cutting) a fence. Notice how their faces glow brighter than their clothing. That's because their faces are warmer than the outside of their shirts and pants.

Infrared radiation

The mysterious binoculars I used at the border were an optical system that could see infrared light. Infrared is light that has a wavelength longer than that of visible light. It is often called "IR." The longest wavelength visible light that we can see has a wavelength of about 0.65 microns. Infrared light has a wavelength from 0.65 microns up to about 20 microns. Since its wavelength is longer, its frequency is *lower* by the same factor.

[1] This is not the place to judge the wisdom of the border policy in 1989. A few years later, the border was tightened. But in 1989, I did ask one border patrolmen what he thought of those trying to sneak in to US. "They are really decent people," he said. "They come here, work hard, and send most of their earnings back to their families in Mexico. I wish I could get my son to work that hard." The life of the border patrolman struck me as being similar to that of Sisyphus. And, as Camus argued in his essay, "The Myth of Sisyphus," Sisyphus was happy.

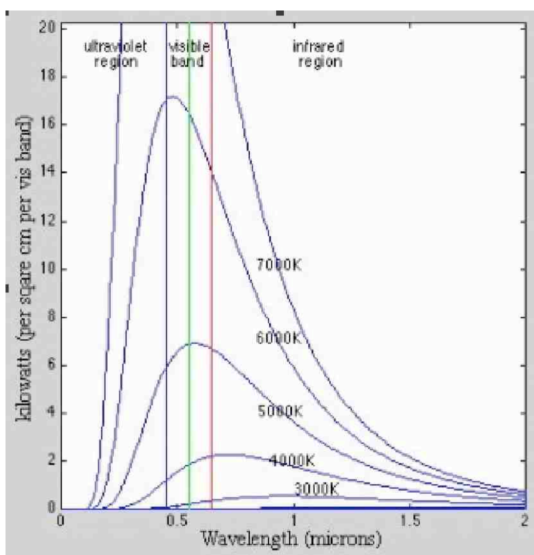
We humans emit infrared radiation because we are warm. The electrons in our atoms shake, since they are not at absolute zero. A shaking electron has a shaking electric field, and a shaking electric field emits an electromagnetic wave. The effect is analogous to the emission of all other waves: shake the ground enough, and you get an earthquake wave; shake water, and you get a water wave; shake the air, and you get sound; shake the end of a slinky, and a wave will travel along it.

The result is that everything emits light, except things that have temperature at absolute zero. Everything glows -- but most things emit so little light, that we don't notice. And, of course we don't notice if most of the light is in a wavelength range that is invisible to the eye.

What are some of the things that we notice when they glow from heat? Here are some: candle flame, anything being heated "red hot" in a flame, the sun, the tungsten filament of a 60-watt light bulb, an oven used for baking pottery. This glowing is often referred to as "**thermal radiation**" or as "heat radiation."

Thermal radiation and temperature

The amount of thermal radiation can be calculated using the physics laws of thermodynamics. The results are shown in the plot below. The horizontal axis is wavelength, and the vertical axis is the intensity of radiation emitted in a square meter. You'll notice that the units are kilowatts per square centimeter in the visible band.



Let's examine this plot, because it tells us a lot about thermal radiation. The straight vertical lines show the wavelengths that correspond to blue, green, and red. Light that is within these lines is visible; we'll call that the **visible band**. The light at smaller wavelengths is invisible ultraviolet light; the light at longer wavelengths is invisible (except to those special binoculars) infrared light.

Each curve is marked with a temperature. The lowest temperature is 3000K; the highest is 7000K. So only really very hot temperatures are present in this plot.

Red hot

Look at the curve for 3000K. It has very little power in the visible band. Most of the power is in the infrared region. And the light in the visible band is stronger in the red than in the blue. An object that is heated to 3000K glows red. We say it is "red hot."

White hot

Now look at the curves for 5000K and 6000K. The temperature of the surface of the sun is near the 6000K curve. Note that there is a lot of red, green, and blue. Although the blue is higher, the levels are all high. It is this almost-equal combination of red, green, and blue, that we call white. The sun is white hot. (I think it is fascinating that with all the nuclear processes going on within the sun, in the end, it is only the temperature that creates the light!)

Blue-white

The plot doesn't show the top of the 7000K curve, but you can guess that the blue part is the most intense at this temperature.

The fact that the color changes with temperature is summarized by the following important law: we can calculate the wavelength L of the most intense light from the temperature from the color law[2]:

$$L = 3000/T$$

In this equation, if T is in degrees Kelvin, then L is in microns. So, for example, if the temperature is T = 6000, then the maximum emission should occur at 3000/6000 = 0.5 microns. You already knew this was true (the sun is nearly 6000K, and sunlight is about 0.5 microns). We'll find this law very useful when we get back to explaining the glowing immigrants.

There is a surprise in this law. Most people think of "red" as hot, and "blue" as cool. That is the way the terms are used in art, and they derive their sense from flames and water. But for flames, the hottest flame glows "blue hot", not just "red hot." Gas stoves usually give off a blue flame; candles, which are cooler than gas stoves, give off a red flame. Potters can estimate the temperature of their ovens by the color of the glowing stones that line it. Astronomers can use the color of stars to estimate their temperature.

Here is the physics behind the law. When things are hotter, the electrons in them shake faster. Remember that it is the shaking of electrons that creates the electromagnetic waves. Hotter electrons give higher frequency radiation. Higher frequency is shorter wavelength.

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[2] In physics texts the color law is called the "Wien Displacement Law."

Total power radiated

One thing that is pretty clear from the plots is that when objects get hot, they emit much much more radiation. Look at the total radiation emitted at 3000K, and compare it to the amount at 6000K. The amount at 6000K is much more. Actually, it turns out to be 16 times more! The rule is that the total amount of radiation is proportional to the fourth power of the temperature[3]:

$$P = A\,\sigma T^4$$

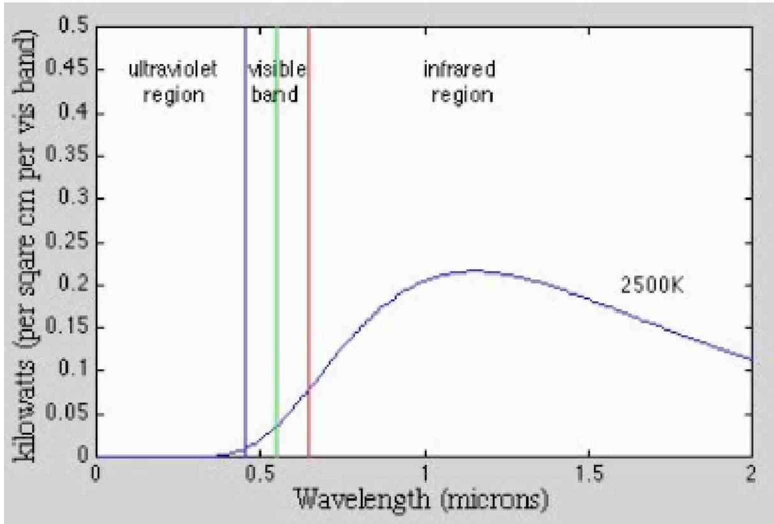
In this equation, A is the area in square meters, T is the absolute Kelvin temperature, and σ is a constant = 5.68 $\times 10^{-8}$. But the important fact is the fourth power. This means that if something is twice as hot, the radiation it emits is increased by a factor of $2^4 = 16$. If it is three times hotter, the radiation is 34 = 81 times stronger. So the amount of radiation increases a lot when the temperature goes up just a little.

Exercise: Work out how much the radiation increase if the temperature goes up a factor of 20, from (for example) 300 K (your temperature) up to 6000 K (the temperature of the sun's surface).

Tungsten light bulbs

Ordinary screw-in light bulbs have a hollow glass sphere with a small tungsten wire inside. Electricity flowing through the wire makes it very hot, typically about 2500K. The light from such a filament has much more red light than blue light. Since the previous plot doesn't show the line at 2500K very well, I've replotted it below showing *only* the power emitted for a 2500K object.

[3] In physics texts this law is sometimes called "Stefan's Law, and σ is called the "Stefan-Boltzman constant"



Remember, we see light only if it is in the visible band. So it isn't really "white". Most people can see that, especially if they compare the light from a tungsten bulb to the light from a fluorescent light, or that from the sun. Light from a tungsten bulb is "reddish." This color tint is exaggerated even more by photographic film (which is extra sensitive to red light). If you use ordinary "outdoor" film for something that is illuminated by a tungsten bulb, the photo will look unpleasantly red.

The fact that it is reddish makes many people think they look healthier in the light from an ordinary light bulb. Bulbs used for photography usually have higher temperatures, typically 3300K, in order to have more green and blue, but even so, they give reddish photographs unless additional correction is done.

How much energy is radiated by a light bulb? If you break open a 100 watt bulb (as I just did) then you'll find the filament has a diameter of about 1/10 mm, and a length of about 20 mm. Counting both sides of the filament, the area is about 4 square mm = 0.04 square centimeters. If it operates at 2500K, then the power emitted in the visible band averages about 0.04 kW = 40 Watts per square cm, so the power is 40 x 0.4 = 16 watts. Yet the bulb is labeled as being a 100 Watt bulb. Are they lying?

No. The label on the bulb tells you how much electricity you will use to light the bulb. It doesn't tell you how much light is coming out. Because most of the light emitted by a 100 Watt bulb is emitted into the invisible infrared region, and (for this bulb) only 16% is in the visible. The rest of the energy is emitted as invisible infrared radiation. It is absorbed by the room, and converted into heat, but it provides no illumination that the eye can see.

Some cameras can see this infrared radiation. They have special settings for photography in "total darkness." But what is total darkness for us (meaning no visible light) is not total darkness for them, since their sensors can "see" the infrared radiation. Such cameras often have small infrared lights on them to provide the light and illuminate the object that the camera is viewing.

When you use such a camera, the viewfinder will turn the infrared signal into a visible image. But, of course, there is no color, because all the camera is detecting is infrared. It does not detect how much red, green, or blue light is reflected off the object, only how much infrared is reflected.

heat lamps

Suppose we make a lamp that operates at about 1500 to 2000 K. The amount of visible light will be almost zero, and they there will be considerable infrared emission. Such lamps are sold, and called "heat lamps." The watts that are emitted are mostly invisible, and yet they will be absorbed on your skin. A little bit of visible light is still emitted, and this is usally seen as a dull red glow. You can get the same warmth by sitting in front of a bright lamp. The advantage of the heat lamp is that you can warm part of your body without having a bright, distracting visible light.

Watching Illegal immigrants -- again

We are back to the example that I used at the beginning of the chapter. If everything that is hot, glows, let's think about humans. Our temperature is about 98F = 37C = 316K. But our skin is cooler, about 85F = 29C = 302K which we'll approximate as 300K. Let's first figure out the wavelength that we radiate, from the color law. Plugging in, we get that the wavelength is L = 3000/300 = 10 microns. That is pretty long wavelength, but it is still considered to be in the infrared region.

How much power is emitted? Let's use the total power law to compare it to power emitted at the surface of the sun. Instead of 6000K, the temperature is 300K, a factor of 20 less. So the power emitted should be less by a factor of 20 to the 4th power, i.e. by a factor of 20x20x20x20 = 160,000. So instead of emitting roughly 16 kW = 16,000 Watts per square centimeter (read off the chart), we should emit 16,000 divided by 160,000 = 0.1 W per square centimeter. What is our area? I estimate that I have a total surface area of about 500 square centimeters. So my total radiation should be about 50 Watts.

50 watts of radiation is quite a lot. The number shouldn't surprise you, however. You know that the presence of a person can significantly warm a small room. Moreover, you know that a person, even if inactive, eats about 2000 Calories per day. That is equivalent to a total energy use of about 100 watts. (For the calculation, see the footnote.[4]) What we have shown is as much as 50 W of that is just because you are warm. No wonder it was possible to devise an instrument that could detect this radiation, and make a visible image for me to see through the binoculars. (The infrared radiation was absorbed by a surface, and this was used to create a picture, like a TV picture, which is what I was really looking at through the binoculars.)

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[4] 2000 Calories per day is 2000 x 4200 joules per day = 8.4 x10^6 joules per day. One day consists of 24 hours of 60 minutes, each with 60 seconds, so the number of seconds in a day is 24 x 60 x 60 = 86400 seconds. So the joules per second is 8.4 x10^6/86400 = 97 watts ≈ 100 watts.

Of course, we are usually surrounded by objects (e.g. clothing, a house, the ground) that is only a little cooler than we are, so we absorb radiation from them. So we don't have to supply all the energy from food. Yet this number illustrates why humans can barely survive on a thousand Calories per day. They burn them just to keep warm. In the United States, a teenager consumes about 3000 Calories per day, and an adult about 2000.

Sleeping under a clear sky and getting wet from morning dew

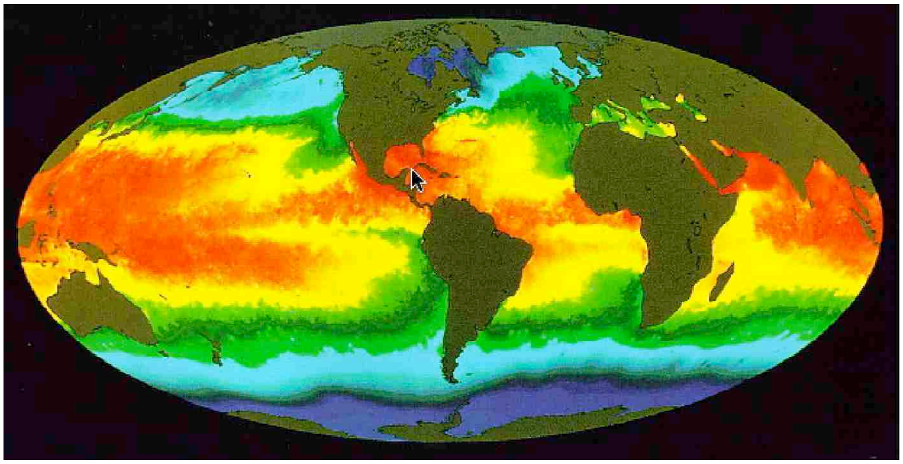
When I go backpacking, I often sleep out in the open without using a tent, so I can watch the stars (and look for meteors). But I learned the problem with doing that: in the morning, the outside of my sleeping bag would be covered with dew. I'd have to wait until I had some direct sunlight, to warm up the bag and let it dry out. However, I found that if I slept outside, but under the cover of a tree, I wouldn't be wet in the morning. (But I also couldn't see as many meteors.) What was happening?

The answer is that the tree, unlike the night sky, radiates infrared radiation just as I do (although not as much, since it is a few degrees cooler). So the outside of my sleeping bag was kept warm by the tree. When I have nothing but black sky above (with stars), then I radiate infrared radiation into the sky, and nothing comes back (except a little star light, but that isn't much). So the surface of my bag gets much colder when it is under a night sky than when it is under a tree. Water vapor tends to condense (form dew) on cool surfaces.

A similar effect occurs under a cloudy sky. Some people say that a cloud acts as a "blanket" but that doesn't really explain what is happening. What really is happening is that the cloud, which is thick enough to be opaque, radiates infrared radiation at me, and that partially balances the infrared radiation that I emit, so I don't get as cold.

Remote sensing of the Earth

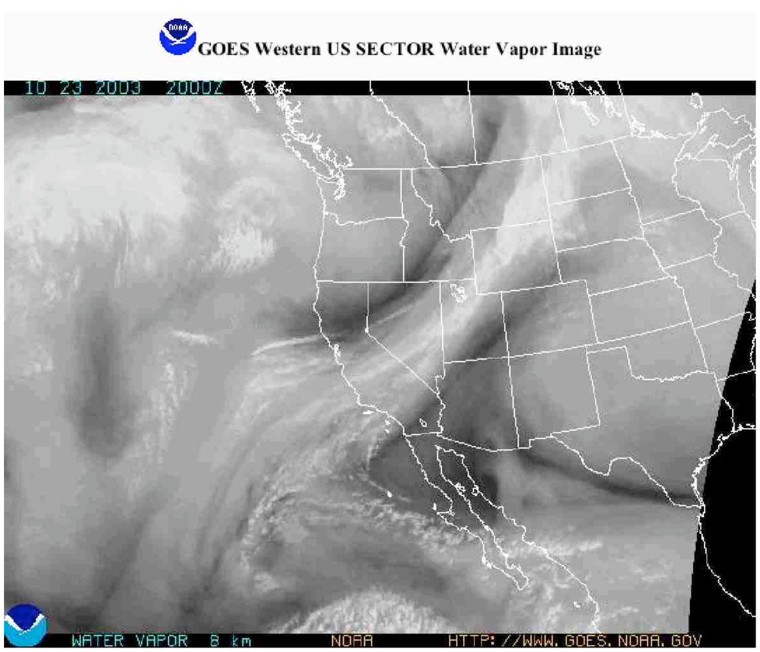
Infrared satellites can measure the temperature of the surface of the Earth by the amount of infrared radiation emitted. The image below shows the temperature of the ocean surface (called SST – for sea surface temperature) measured from satellites.



(from pao.gsfc.nasa.gov/gsfc/earth/pictures/earch2.htm)

Weather satellites

Modern weather satellites take images in the visible (wavelength 0.65 microns), the IR (near 10.7 microns). The visible measurements are useful for observing clouds, and the IR can be used to measure the temperature. Some modern satellites also include a kind of infrared multispectral – a sensitivity at yet other wavelengths that can give additional information about the surface. One of the most important of these is a camera that is sensitive at 6.5 microns. This is a wavelength that can detect water vapor. Air, that is high in water vapor, will form clouds (and rain) if it is cooled, so a photo showing the flow of water vapor can be used to help predict where storms might form. Such an image is shown below, with a map superimposed in white.



(from www.unidata.ucar.edu/community/committees/users/prop.sat.06.03.html)

Military special ops

The United States Special Operations Command has a motto: "We own the night." The reason for this motto is that they plan to do almost all of their operations at night. They do all their training at night using night vision viewers that are worn over their eyes. Some of these are simply "image intensifiers" -- that is, they magnify the existing light. Others are infrared (IR) viewers. The infrared viewers work in two ways. The ones that are sensitive to "long wavelength" -- about 10 microns -- pick up the infrared radiation emitted by warm people. But they also have "short wavelength" IR viewers. These pick up radiation between 0.65 and 2 microns. (That's still longer than visible light, but shorter than the long wavelength IR.) What good is that? People don't emit much light in that range. Well, it wouldn't be very useful, if they didn't carry infrared flashlights. These emit a light that can't be seen by the enemy, but can be seen through their infrared viewers. I found a set of such goggles, with built-in light, for sale on the web. They operate at a wavelength of 950 nm = 950 nanometers = 0.95 microns. That's almost twice the wavelength of visible light.

Infrared viewers are also valuable for detecting anything that is warm -- warmer than the surroundings, that is. An infrared viewer, looking at an automobile, can tell if that automobile has been operated recently, because it shows the warm region near the engine. An infrared viewer can detect the heat from a campfire long after it has been "extinguished." It can tell which caves have people inside them, by the fact that those are the caves that have warm air coming out of them. The US military knows that the infrared viewers will be even more effective when the ground is covered with snow, because the background "clutter" from ground emissions will be reduced. That is part of the reason that the United States military does not appear to be anxious to get their military operations concluded before winter. They probably believe that it will be easier to locate bin Laden when the snow covers most of the ground.

In addition to ground troops, the United States operates unmanned aircraft called "drones" that carry infrared imaging devices. The most impressive of these is the "Global Hawk" drone. If you want to see a very strange-looking aircraft, look at the Global Hawk photo. This drone can fly unmanned, directed by GPS, from Germany to Afghanistan, then circle over Afghanistan for 24 hours, and then fly back. In the meantime, its cameras (infrared and visible) and radar is constantly sending images back to the US by radio. It flies at 65,000 feet, the same altitude as the U-2, and far above the ability of the Taliban to shoot it down. In fact, it is so high, that they probably will never know when it is watching them. (From the angle of the tails, it appears that it incorporates Stealth technology, to make its radar signature weak. That is also the probable reason for the engine being mounted on the back of the plane, where it will not be easily visible to ground radar -- after all, it might act as a corner reflector!

Stinger missiles

One of the real worries of the American troops in Afghanistan is the threat of Stinger missiles. These are missiles that can be launched from a device held by a single soldier, aimed at a low-flying airplane or helicopter. They weigh only 35 pounds, and can reach up to about 10,000 feet. These missiles were given to the Taliban by the United States back in the days when the U.S. was trying to undermine the Russian-imposed government. Now the Taliban plans to use them against us. You can read more about the Stinger at the web site put up by the Federation of American Scientists. (Actually, the FAS web site is a very good site for information on national security issues.)

The reason that I am discussing the Stinger missile in this section is because of the way they work. They have on them a device that steers them towards anything that is emitting strong infrared radiation. That means anything hot, and up in the sky that usually means the tail pipe of an airplane or helicopter. In order to prevent a stinger from hitting the airplane, the pilot will sometimes drop hot flares, and the missile will choose to go after them instead. But some of the stinger missiles have special devices to prevent them from being fooled. Because the Stinger is so small, it can change direction more rapidly than the helicopter, so it is hard to outmaneuver.

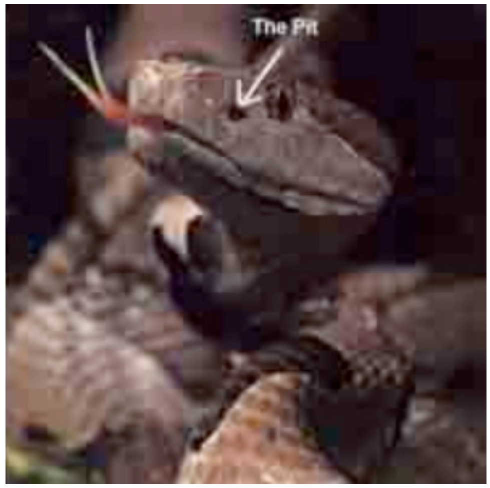
The U.S. gave many Stinger missiles to the Afghanistan Taliban in the days when they were opposing the Russians. We fear now that such missiles have found their way into the hands of terrorists, and could be used against both commercial and military aircraft.

Pit vipers and mosquitoes

Pit vipers are highly poisonous snakes that have regions on the sides of their faces called "pits". What makes them interesting for us is that the pits can detect infrared radiation! So the pit viper can sense the closeness of prey even in "total darkness" (which refers, of course, to the absence of visible light). Below is a photo of a pit viper, borrowed from http://www.psych.yorku.ca/people/faculty/harris/2220/viper.jpg.

Mosquitoes are also attracted to infrared radiation. Here is a site I found on the web that discusses this: http://www.howstuffworks.com/mosquito3.htm

Why do other animals not detect infrared radiation? Probably because their eyes work OK. It is very hard for a warm-blooded animal to have an infrared sensor, since the animal is emitting so much itself. The pit viper, of course, is a cold-blooded snake.



Infrared radiation, even though it is invisible to our eyes, is just another form of light. It is similar enough (just a little longer wavelength) that it tends to bounce off glass and metal surfaces in the same way that visible light does. We can bounce infrared off mirrors, and focus the light just light. See the description of the infrared reflection demonstration.

UV – and "blacklights"

"Blacklights" are lights that emit little or no visible light, and yet make other things glow. You can buy a black light at many hardware stores, and the salesman will probably warn you that they are dangerous to look at. The reason is that black lights are actually glowing brightly at ultraviolet wavelengths, which are invisible to the eye, but still carry energy. The ultraviolet rays, abbreviated UV, can burn the retina of your eye, and on the skin can cause sunburn and cancer.

Some chemicals, when they absorb UV, then emit visible radiation. We call such chemicals "fluorescent" or "phosphorescent." A fluorescent light is called that because of the interesting way it works. Electricity flowing in the gas of the light emits UV radiation. That radiation is absorbed by a coating on the inside of the light bulb, and is reemitted as visible light.

The good quality "black lights" that you can buy at a hardware store consists of an ordinary fluorescent bulb with the fluorescent coating removed (or, more likely, just never put there). A cheap (and not very satisfactory) black light can be bought at some stores, but it consists of an ordinary light bulb painted black. Actually, it is black only to visible light, and the UV radiation emitted by the filament passes on through. Black lights made in this way emit only a tiny amount of UV, and are not any fun to play with.

Black lights are popular during Halloween because of the way they can make certain things glow in an otherwise dark room. They are extensively used at Disneyland for the same effect. Geologists use black lights to detect certain minerals, which are known to fluoresce. If you've been to Disneyland, or some other exhibit that uses black lights, you've probably noticed that some clothing, particularly white clothing, glows very brightly, while colored clothing doesn't. Why is that? The answer to the question is surprising, so I add another section:

Whiter than white

There was an advertisement, a few years ago, for a clothes washing soap that made your clothes "whiter than white." That sounds absurd, doesn't it? Many physicists instinctively thought that the ad was nonsense, and simply ignored the laws of physics. If all the light that is incident on a surface is reflected, then we say that that surface is white. How could anything be whiter than white?

It turns out that the physicists were wrong. Some clever dish soap people figured out a way to make clothing whiter than white! They added a fluorescent chemical to their soap, and made it into a chemical that stuck on to the clothing. So after washing your white shirt, it would have this stuff stuck all over it. That's terrible, you say -- the washing was making the shirt dirty! Yes, but it sold soap!

Why? How? Well, when people (mostly women, in those days) washed their spouses (mostly husbands, in those olden times) white shirts, they noticed a difference. Hold the shirt out in sunlight, and it is brighter! In fact, you might even say, it looked "whiter". The shirt was reflecting all the red, green, and blue light, just as before. But in addition, it was absorbing the invisible UV radiation, and reemitting it as visible light. It was glowing, not in the dark, but in the sun! Anybody who looked at the shirt would notice it was brighter, and therefore (by the logic of that time) cleaner (even though it had all this chemical stuck to it).

The shirt manufacturers caught on too, and they started adding fluorescent dyes to their white fabrics. Out in the sun, which contains lots of UV (see the diagram for T = 6000K), the brightness is very noticeable. It has less of an effect indoors, since tungsten filament bulbs operate at about 3000K, and don't have very much UV. (Again, check this in the diagram.)

Sunburn

UV light is responsible for sunburns, suntans, "windburn," and much of skin cancer. It can also be used to kill bacteria, and that makes it very useful in operating rooms, and for killing organisms found in water in remote villages in India.

The most potent form for burning and cancer has a wavelength of about 300 nm. This kind of radiation is absorbed by ordinary window glass (window glass is "black to UV"). Sunglasses are much thinner than window glass, so UV gets through, and that can cause sunburn on your eyes; most sunglasses these days are made of a special gas that absorbs even better than window glass, and they are labeled with their UV absorption capabilities.

As I mentioned earlier, fluorescent light bulbs contain a gas that emits UV radiation when electricity flows through them. The glass on the bulb is coated with a phosphor, which is a material that absorbs the UV and emits visible light. If you don't put in the phosphor, and use thin glass (so the UV isn't absorbed) then you get a UV lamp. Such lamps are used to kill bacteria and to make objects fluoresce.

One of the most fascinating uses has been in rural India and other undeveloped areas, where such lamps are being installed to shine on water that is pumped from contaminated rivers and wells. A few seconds under an intense UV lamp can be enough to cause mutations in the DNA of the bacteria, and as a result they cannot reproduce. The water must be passed under the UV lamp in a thin layer so that there isn't enough water to absorb the UV. The lamp is powered by a gasoline engine with an electric generator.

windburn – and viewing eclipses of the sun

Your skin cannot tell when it is in bright sunlight except from the warmth. If it is a cold day, and particularly if the wind is blowing, your skin might feel cool, and you won't realize that you are getting a sunburn. Even more deceptive is a cloudy day. How can you get "sunburn" if you can't see the sun? Well, you can. Just as the visible light isn't blocked but just spread out by the clouds (cloudy days can still be quite bright), so is the UV. As a result, on a cool, breezy, cloudy day, you can get a bad sunburn without realizing it. Such a burn is often called a "windburn", which gives the misleading impression that you are being burned by the wind. You are being burned by UV, and it is the wind that keeps you from noticing.

During an eclipse of the sun (when the moon blocks the center of the sun), people like to look at the corona, the glowing gas that surrounds the sun and is usually hard to see because the sun is so bright. You can do this by looking through a piece of dark glass.

But when you do this, you better make sure, first, that the glass is also dark in the UV. If it isn't, then you will be looking at a bright UV source, and that can badly sunburn your eye.

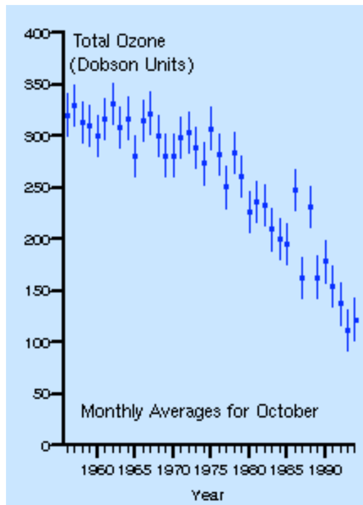
The ozone layer

When sunlight passes through air, the UV tends to break up some of the O_2 molecules into individual atoms, O and O. These atoms attach themselves to non-broken O_2 molecules to make O_3, also known as ozone. Ozone is a very strong absorber of UV radiation from the sun.

If we didn't have any ozone, then we would expect the UV from the Sun to make it throughout the atmosphere. But when ozone forms at high altitude, it prevents the UV from reaching low altitude, and little UV makes it to the ground, and as a result little ozone forms at the ground. Most of the ozone is in the "ozone layer" at an altitude of 40,000 to 60,000 feet.

High altitude ozone protects us from the UV. If the ozone layer were to vanish, then the UV would reach the ground, and problems with sunburn and skin cancer would be exacerbated.

Over Antarctica, the sun rises only once every year, and when that happens, the ozone layer forms. This formation is studied with UV sensors in Antarctica. In the 1970s, scientists noticed that the amount of ozone was decreasing every year. This decrease became known as the "ozone hole." A plot of the ozone depletion is shown in the diagram below.



Was this decrease natural? Would it spread to the entire globe, or be restricted to Antarctica? Nobody knew, although some people thought it might to due to a pollutant introduced into the atmosphere by humans. In fact, that is what it turned out to be.

Freon and CFCs

A chemical called "Freon" was in wide-spread use, in refrigerators and air conditions, and as a solvent (cleaning agent). But Freon was a compound in a class called CFCs (for "chlorofluorocarbons) containing the elements chlorine and fluorine, and it was highly stable; it didn't decompose readily, and when it leaked into the atmosphere (from defunct refrigerators and air conditioners), it stayed there for a long time. It eventually diffused into the high atmosphere, where it was hit by ultraviolet light, and broken into its constituent chlorine and fluorine atoms. It turns out that chlorine and fluorite are very effective at turning ozone back to ordinary oxygen, O_2. So Freon was, in effect, destroying the ozone layer.

The biggest effect was over Antarctica. Nobody knew why, until atmospheric scientists realized that certain crystals of nitric acid formed there in the early spring, and on the surface of those crystals, the chlorine and fluorine was far more effective at destroying the ozone. So the biggest effect was seen first over Antarctica.

Nobody knows for sure whether the destruction of ozone would continue until it reached more populated areas, but the world was sufficiently worried that it outlawed the use of

Freon. As a result, we expect that the ozone destruction will soon be halted, at least as soon as the existing Freon in the atmosphere is used up.

Freon had also been used as a propellant for aerosol cans, for everything from shaving cream to insect repellant. It has been replaced for that purpose with other gases, including nitrous oxide. Some people still boycott aerosol can products because they don't realize that the new ones are no longer dangerous to the ozone layer.

Some people say that the real lesson from this experience is that we can affect the atmosphere with human pollution, and that the effects are sometimes larger than we calculate. So we should be cautious. That brings us to another different, but similar problem – the potential atmospheric pollution from the burning of fossil fuels.

The warmth of the Earth

The Earth is warmed by the sun. The temperature of the Earth is determined by the fact that the power of the incoming sunlight is balanced by infrared emission. It would just get warmer and warmer if it didn't have a way to lose that absorbed energy. But it does – infrared emission. If we assume that all the radiation that hits the Earth is absorbed, and is equal to the radiation that the Earth emits, we can calculate the following surprising result: the temperature of the Earth is approximately 1/20 the temperature of the Sun. (For the calculation, see the footnote.[5]) That seems perfect: the Sun has a temperature of 6000 K, and that means the temperature of the Earth should be about 6000/20 = 300 K. And that's what it is!

That is a remarkably simple way to understand the average temperature of the Earth. If we were further away (e.g. Mars) we would be colder. If we were closer (e.g. Venus) we would be hotter. As it is, we turn out to be just right.

There was, however, one small mistake in the calculation. I assumed that all of the sunlight that hits the Earth is absorbed. But we know that only about 60% is absorbed; the rest is reflected. (The reflected amount is called the Earth's *albedo*.) That means that the temperature of the Earth should actually be about 30 C colder, and that puts it below freezing. Life could not exist on Earth, if there weren't additional warming. That comes from something called the *greenhouse effect*.

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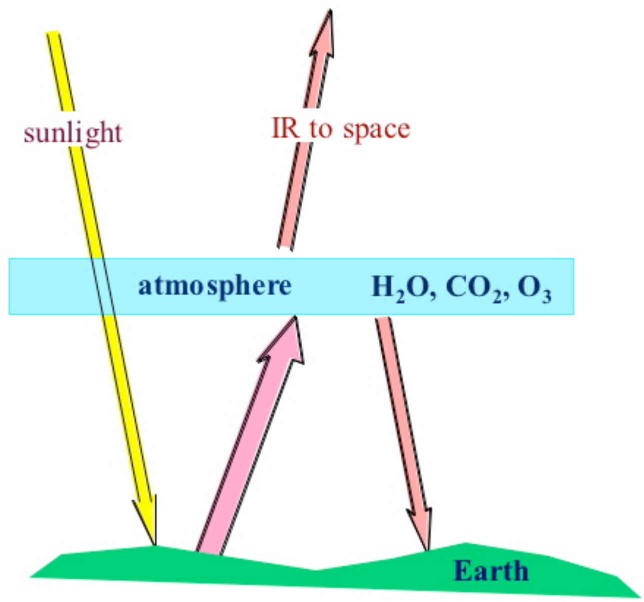
[5] The following optional calculation is for those familiar with 3-D geometry. T_S = Sun temperature; T_E = Earth temperature; Rs = Sun radius; Re = Earth radius; D = Earth-Sun distance. Power radiated by Sun = Ps = $4 \pi Rs^2 \sigma T_S^4$. Power absorbed by the Earth is Pe = Ps $(\pi Re^2)/(4 \pi D^2)$. Power emitted by the Earth is Pe = $4 \pi R_E^2 \sigma T_E^4$. Solving these equations gives $T_E = T_S \text{ sqrt}[R_S/(2D_S)]$. We know (from looking at the size of the Sun) that $R_S/D \approx 1/200$. So $T_E = T_S/20$ = 6000/20 = 300 K. For Mars, D is larger; for Venus, D is smaller.

The Greenhouse effect

The Greenhouse effect has been in the news a lot, and may be in the news even more in the future. It is not a speculative or hypothetical effect. It is what makes the Earth warm enough for life. If the Greenhouse effect increases, then we expect an intolerable amount of global warming, enough to make many agricultural areas into deserts. The effect is illustrated in the following diagram.



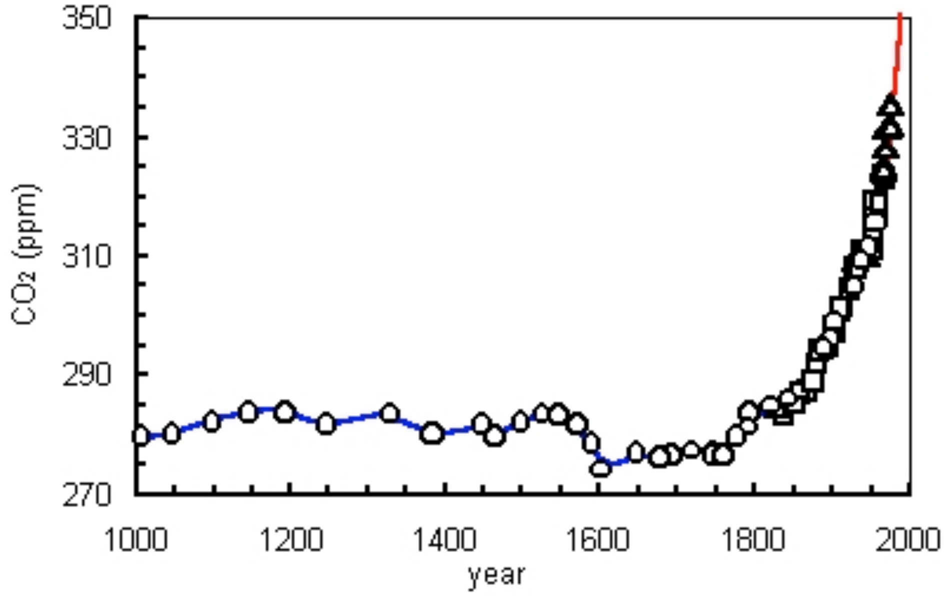
Sunlight hits the Earth, the Earth gets warm, and it emits IR (infrared) radiation. With no atmosphere, that radiation would just go to space, and our temperature would be below freezing. But, as you can see in the diagram, most of that radiation is absorbed by the atmosphere. That's because water vapor (H_20), carbon dioxide (CO_2) and ozone (O_3) are effective absorbers of IR. So the atmosphere gets warm, and it radiates its own IR. Half of that goes to space, and half comes back to Earth. So the Earth is warmed both by the Sun and by the atmosphere. That warms the surface enough to keep the oceans from freezing.

The same thing happens in a garden greenhouse. Sunlight comes through the glass, and the infrared heat cannot escape. That's why this phenomenon is called the greenhouse effect. These days, more people have experience with automobiles in parking lots. Sunlight, entering the window, heats the interior, and the heat cannot escape. The result is that the interior of the car gets very hot. Perhaps a more up-to-date name for the phenomenon (at least in the U.S.) would be "the car in the parking lot effect."

Changes in the Greenhouse Effect – and global warming

The greenhouse diagram showed all the IR from the Earth being absorbed by the atmosphere, but that was an exaggeration. Some leaks through, so the greenhouse warming is not as much as it would otherwise be. But if we add additional gases to the atmosphere, particularly more water vapor and carbon dioxide, then the atmosphere will absorb more.

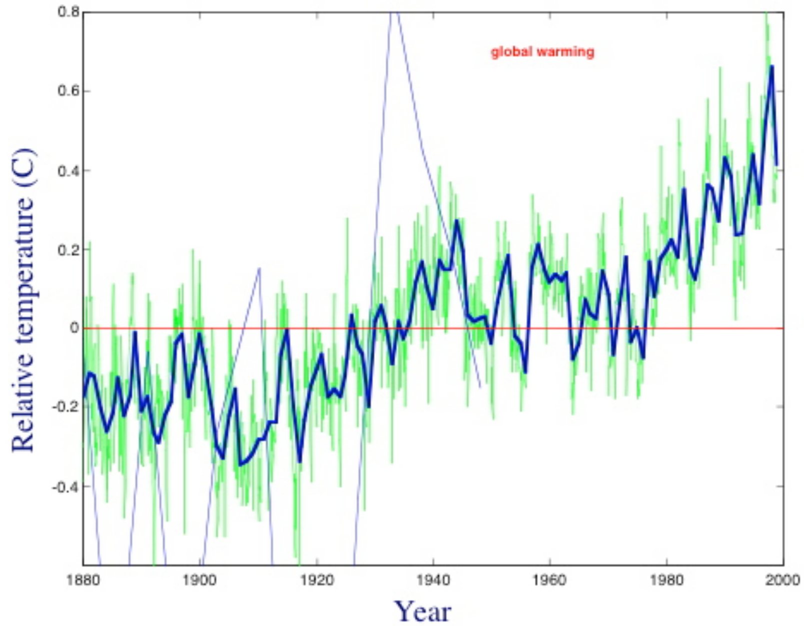
We happen to be doing just that. The amount of carbon dioxide in the atmosphere for the past few hundred years is shown in the diagram below.



(borrowed from www.2think.org/ keeling_curve.shtml)

Note the suppressed zero. For about 800 years, the carbon dioxide in the atmosphere was pretty steady at about 280 parts per million (i.e. it was 2.8×10^{-4} of the atmosphere). Then, sometime before 1900, it began to go up. Many people think this was from the increased use of fossil fuels. We used coal to produce "coal gas" used to light streets and homes. Then oil was discovered, and that was used for lighting and heating. The development of the automobile occurred simultaneously with the discovery of even greater oil reserves. (The Rockefeller oil fortune was made even before the automobile.) Thus, it is plausible that the increase is entirely due to humans – but this is not known for sure.

Since carbon dioxide is good at absorbing IR, the increase could result in a more effective greenhouse effect, and give rise to global warming. In fact, temperature records show that just such a warming is taking place (see the figure below). The rise in temperature in the last century has been about 1 C. Many people (not all) think that is due to carbon dioxide introduced into the atmosphere by humans.



Why don't all people accept this conclusion? The fundamental reason is that the amount of warming we have experienced is much greater than you would expect from the carbon dioxide introduced into the atmosphere. That should have been only 0.1 or 0.2 C, yet the observed warming is 1 C. But there is a possible explanation for that too. As indicated in the diagram, another potent greenhouse gas is water vapor, H_2O. Suppose a little bit of warming from carbon dioxide meant that more water would evaporate, and that would create even more warming. Thus a little CO2 could have a much bigger effect because of the amplification of its effect by water.

There is a big unknown that makes this question even muddier. If we have more water vapor in the atmosphere, wouldn't that make more clouds? Clouds reflect sunlight, and so the clouds could cause cooling. Unfortunately, the process of cloud formation is so complicated that we don't know if more water vapor would create more clouds or fewer. Scientists are trying to answer this question with measurements, and with large computer models of cloud formation, but it is one of the most difficult issues to answer.

The general consensus is that the increased carbon-dioxide levels appear to go up more or less at the same time as we have seen global warming, and therefore it is a plausible connection. It appears that carbon dioxide emissions will grow (unless we have treaties to stop this) and that suggests that global warming will continue. The best estimates are that at the present rate of increase, the temperature could be several degrees warmer by the middle of the 21st century, and most people believe that would lead to major economic disruption.

Electromagnetic radiation

In the table below, we list all of the forms of light, including "invisible light." Some we have discussed in some detail, including visible, IR, and UV. Two of these, x-rays and gamma rays, were mentioned briefly in the chapter on radioactivity. But look at the list. It is in increasing order of frequency. All the signals shown travel through vacuum at the same speed, 3×10^8 meters per second, equal to 186,284 miles per second, or 1 foot per nanosecond (a typical computer cycle).

name	comments	wavelength	frequency
AM radio	ordinary radio	300 meters	1 MHz
TV, FM radio	higher frequency for more bits/sec	3 meters	100 MHz
microwaves	radar, microwave oven, cell phones	10 cm	3 GHz
heat infrared (IR)	emitted by warm bodies (us)	0.002 cm = 20 μ	15,000 GHz
near infrared (IR)	a color we can't see	1 μ	3×10^{14} Hz
visible light	detectable by human eyes	0.5 μ	6×10^{14} Hz
UV (ultraviolet)	responsible for sunburn. Can cause skin cancer.	0.3 μ	10^{15} Hz
x-rays	passes through water, not bone	10^{-9} meters	10^{19} Hz
gamma rays	emitted by nucleus; can cause cancer; detected from distant galaxies	10^{-11} meters	10^{21} Hz

Radio waves

Radio waves are electromagnetic waves at frequencies between several thousand cycles per second up to tens of millions of cycles per second. At these frequency ranges they can carry only that many bits per second, and that is enough for ordinary radio. The highest frequencies are used for high quality music (FM radio) and TV, since these signals require more information every second.

Because of their long wavelength (3 to 300 meters or more) they spread a lot when they pass through openings. The longer waves can even spread around the curvature of the Earth, so they can be heard at long distances. That's why AM radio usually can be heard further from the transmitting antenna than can FM or TV signals. FM and TV usually require "direct line of sight" since they don't diffract around mountains and buildings as much as the longer-wavelength waves used for AM radio. The only reason that AM radio isn't used for everything is that the lower frequency can't carry as many bits per second, and so the sound on AM radio is not as good as on FM. (Signal compression methods have recently been used to improve this.)

Microwaves

Microwaves are very much like radio waves but with a shorter wavelength, typically only a few centimeters. Microwaves are used in radar, microwave ovens, and cell phones. Just like ordinary radio waves, they travel right though clouds and smoke, and that means they can be used to send signals very reliably. Some of our satellites use microwaves to send telephone and internet signals. Because their wavelength is so small, they can be bounced off dish antennas (and aimed at distant locations) without much spreading. (Recall that the spreading S = L/D. So small wavelength L means small spreading.) A microwave dish acts like a lens. The microwaves are emitted near the focus; they bounce off the dish, and come off parallel, aimed at some distant target.

microwave towers

On mountain tops, you will see towers with small dish antennas that bounce microwaves from one dish antenna to another one that is perhaps 10 to 50 miles away. (The distance is really limited by the curvature of the Earth.) Because of their high frequency, they can carry many telephone conversations or many internet signals simultaneously.

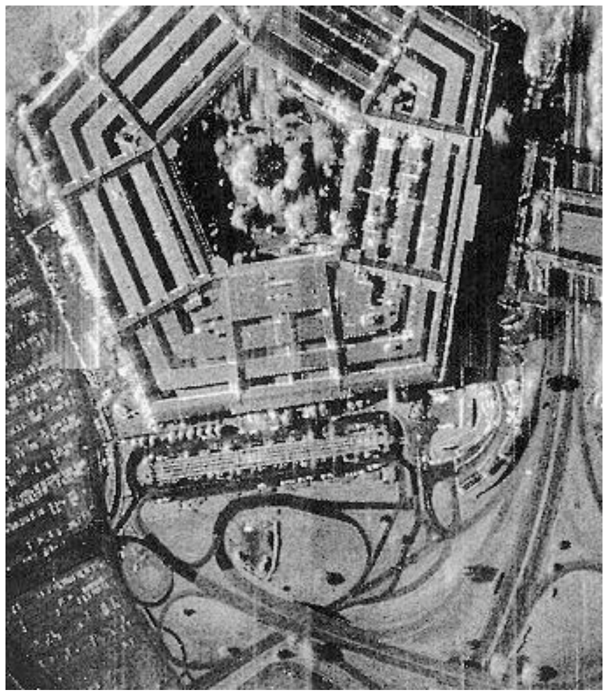
radar

The word radar was originally an acronym for "radio detection and ranging." It is a method of emitting radio waves (primarily microwaves) into the sky, and looking for reflections off metal objects such as airplanes. From the time it takes the signal to come back, the distance to the plane can be measured. Microwaves are used for radar because of their short wavelength. That means that they don't spread too much from a small antenna, so you can aim them accurately and determine the direction of the plane. Of course, it is also important for this application that they travel pretty easily through clouds and smoke.

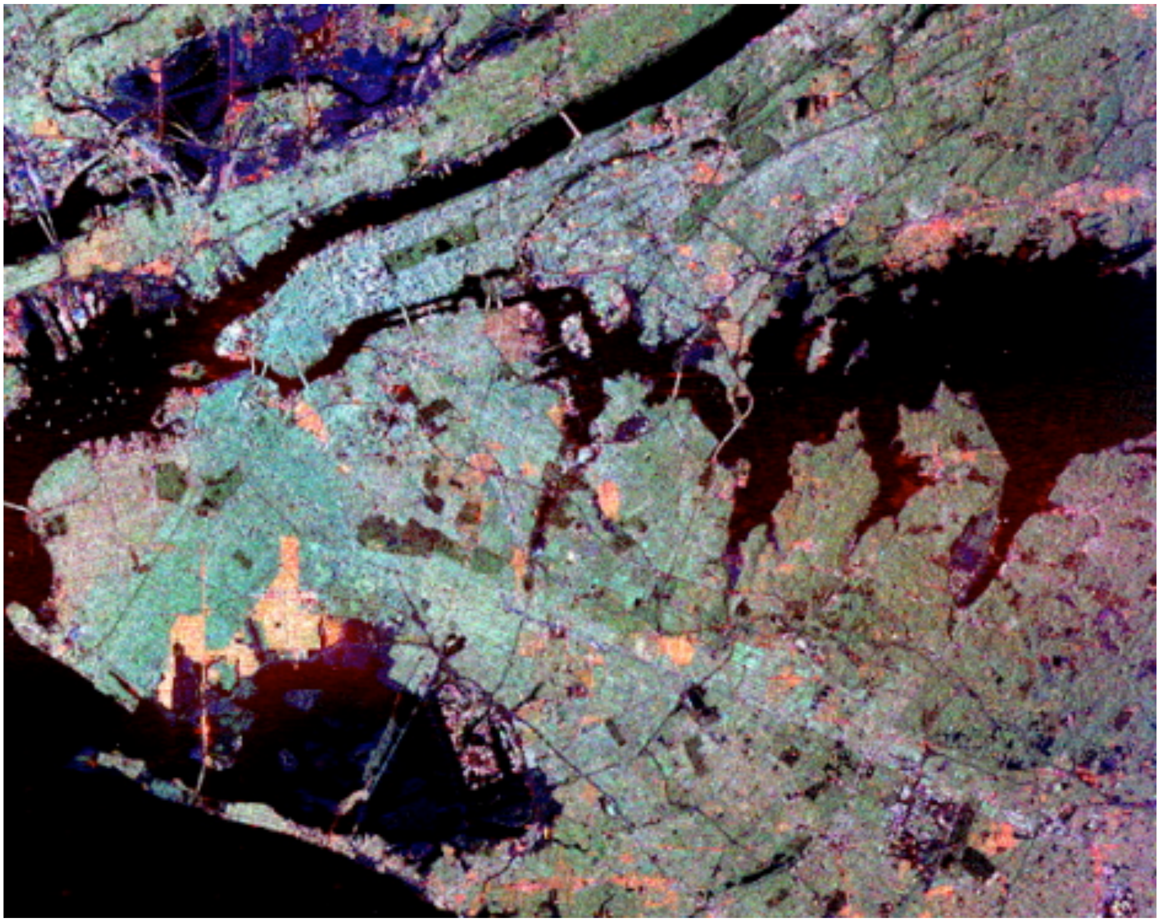
Radar was first used to detect Nazi airplanes during World War II. It probably saved Britain from invasion, in the following way: during the early parts of the Battle of Britain, the Nazis sent numerous bombers to attack London and other cities. Every time they reached the English shore, they were met by British fighter airplanes. The Nazis assumed, incorrectly, that Britain had thousands of such airplanes, since they were always patrolling the coast at the right place. In fact, there were not very many, but radar told the planes where to go to meet the incoming attackers. As a result of this deception, the Nazis overestimated the British strength, and postponed an invasion that probably would have succeeded.

Radar can be used to locate airplanes, missiles, and rain clouds. All large airplanes are equipped with radar to detect other airplanes and stormy regions. You can buy a relatively inexpensive (a few thousand dollar) radar system for your pleasure boat, and use it to spot other boats, and help you get through fog.

Radar is now getting extensive use as an imaging tool and for mapping. It is possible to put radar in an airplane and look down at the ground. The received signal can be used to form an image of the ground. To make it even better, the image can be accumulated as the airplane flies, and the total signal (over five minutes of flight) put together to form the same kind of image that a huge radar receiver would have obtained, i.e. the image that you would have from a radar receiver that is several miles long (as long as the flight path). Such a system is called "synthetic aperture radar", SAR, because it synthesizes the image. Below I show a SAR image of the Pentagon (taken by an unmanned drone), and a SAR image of New York City.



The Pentagon, imaged with synthetic aperture radar (SAR)



New York City, imaed with synthetic aperture radar (SAR). Note the numerous bridges across the East River, and the rectangular Central Park near the top. The colors are false, and were put in to indicate the intensity of the reflection.

microwave ovens – "radar ranges"

The original microwave oven was invented by a man who stood in front of a radar emitter, and found that it warmed him up. For this reason, the original microwave oven was called a "radar range." We now understand that microwaves are absorbed by the water in your body, and their energy is converted into heat. In a microwave oven, the microwaves are confined by metal walls, so they bounce back and forth inside the oven, getting absorbed by whatever water-containing substance is inside.

You are always warned not to put metal inside a microwave oven. There are several reasons for this. The waves can create a high enough voltage across metal parts to create sparks that can do damage. But in addition, the fact that the metal will reflect the microwaves can lead to uneven heating of the food you are trying to cook.

Despite the fact that microwaves can warm you, it is now known to be very dangerous to your eyes. The reason is that the inside of your eyes have no good way to get rid of the heat that microwaves will create there. The man who was standing in front of the radar was lucky that he didn't lose his eyesight.

Low levels of microwaves cause only low levels of heating, and your eyes can handle that with no trouble. Microwaves do not have the ability to damage DNA in the same way as x-rays and gamma rays. Most of the fear that microwaves can cause cancer is simply a reaction to the fact that microwaves are sometimes called microwave radiation, and it the use of the term radiation frightens some people.

X-rays and gamma rays

X-rays and gamma rays are very high frequency, very short wavelength forms of light. We discussed these in the chapter on radioactivity. X-rays are emitted by rapidly accelerating electrons. The x-ray machine that your dentist uses makes a beam of electrons, and shoots them at a piece of heavy metal such as tungsten. When the electrons suddenly stop, the emit x-rays in the same direction that the electrons had been moving.

The same thing happens when a beam of electrons hits the front of a TV screen. X-rays are emitted right towards the viewer. To stop this radiation, a special glass is used in the front of the TV, called "lead glass." As its name suggests, this glass contains a lot of the heavy element lead, and that absorbs the x-rays.

Gamma rays are emitted by nuclei undergoing radioactive decay (i.e., the nuclei are exploding).

Because the wavelength is so short, and the frequency is so high, every wave packet of x-rays and gamma rays contain substantial energy. (Well discuss this further when we get to the chapter on quantum mechanics.) X-rays packets typically contain 50 to 100 thousand eV, and gamma rays 1 MeV or more. This high energy made them appear, to early scientists, to be energetic particles. Indeed, even energetic particles are waves, so the difference between them begins to blur. But unlike protons and electrons, gamma rays and x-rays are electromagnetic waves, i.e. their fields consist of electric and magnetic fields.

The most interesting applications of x-rays and gamma rays are for medical imaging. Indeed, when Roentgen first discovered x-rays, he used them to make an image of the bones of his hand. That so astonished the word, that many people assumed that "Roentgen rays" (as x-rays were originally called) were a fraud. People were unwilling to believe that such a miracle – seeing into the inside of the body -- would be possible.

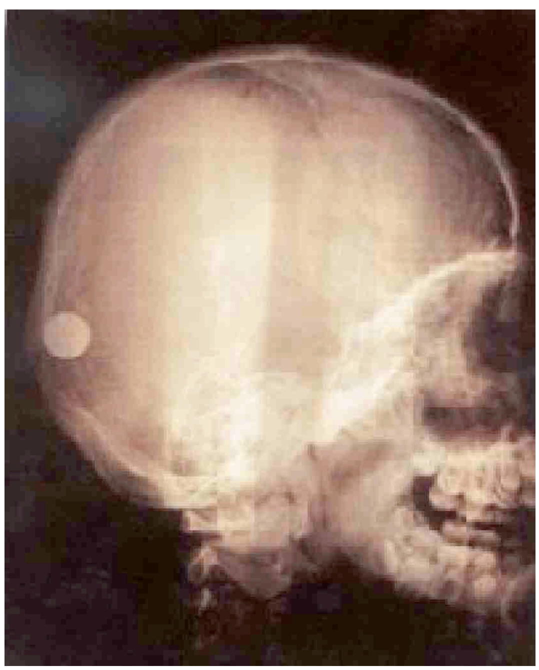
Medical imaging

Anything that can penetrate the body, and which moves in more-or-less straight lines, can be used to get information about what is going on inside the body. The value of that for medicine is obvious.

X-rays

X-ray images are like shadows of semi-transparent objects. They depend on the fact that heavy elements (such as the calcium in your bones) absorb x-rays more readily than do light elements (such as the carbon, hydrogen, and oxygen in your blood and muscles). X-rays are particularly useful for viewing bones.

To take an x-ray image, x-rays are emitted at a point, usually by hitting a heavy material sucgh as tungsten with a finely-focussed beam of electrons. When the electrons suddenly stop, they emit x-rays. The object to be imaged, perhaps a broken bone, or (as in the image below) a head, is placed in between the emitter and a piece of film. (The silver halide in photographic film is exposed by x-rays, and this is still the most popular way to detect them. Electronic recording, such as in a digital camera, are beginning to be used, but they don't offer the high resolution that photographic film does, and most doctors depend on that resolution for their diagnosis.)

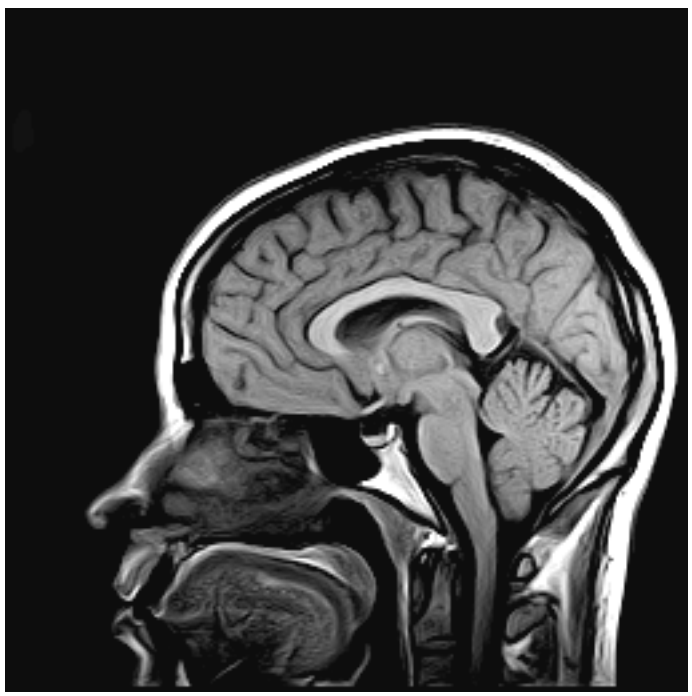


The figure above shows an x-ray image of a human skull. Remember, it is similar to a shadow. X-rays tend to darken the film, so the background is black. The bright parts of the image are the regions in which fewer x-rays got through. So white regions represent bone; that makes the image easy to interpret. Look at the teeth. You can make out the roots. When a tooth has decay, the density of calcium is reduced. This leads to a slightly darker region (more x-rays come through).

X-rays also have applications in industry and in national security. High frequency x-rays and gamma rays can be sent through cars, trucks, and containers (from shipping) to look for heavy materials. They are particularly sensitive to the heaviest elements – such as uranium and plutonium! Thousands of containers enter the US every day, and the government has begun a program to subject as many of these as possible to x-rays in order to intercept such materials.

MRI (formerly called NMR)

The image below is a magnetic resonance image (MRI) of a human skull. If you initially thought it was a drawing, or a real skull that was physically sliced open, then you can probably understand the feeling of people who saw the first x-ray images a hundred years ago. In my mind, the image is a true miracle of modern physics.



Magnetic resonance imaging maps the distribution of hydrogen. The density of hydrogen is greatest in soft tissue (in carbohydrates and in water), and that's why you see the brain and tongue so well. Looks great. But notice that you can't see the teeth, as in the x-ray picture. Teeth do not contain much hydrogen.

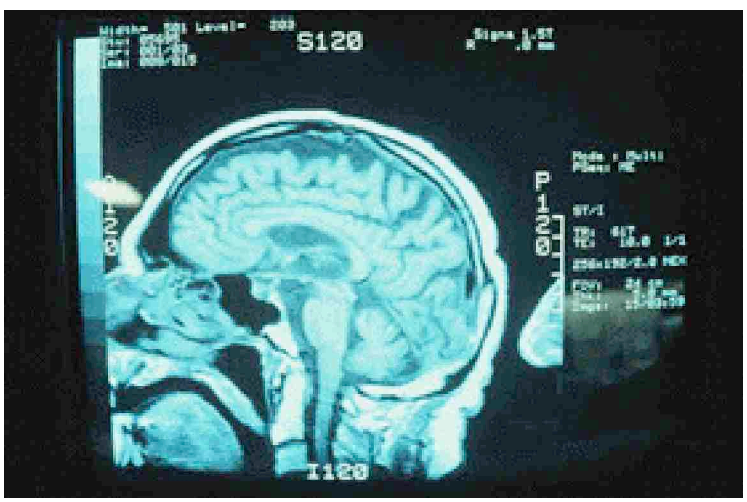
Magnetic resonance imaging was formerly called "nuclear magnetic resonance imaging." However the presence of the word "nuclear" frightened potential patients, and so it was dropped. (I'm not kidding. That's exactly what happened.)

The way it works is by detecting the spin of the hydrogen nucleus, i.e. the proton. The patient is placed in a strong magnetic field, usually inside a cylindrical magnet. (Some patients don't like being placed in such a confined place.) The protons in the patient are also magnets (because they are spinning charges) and the external magnet tends to make them line up in the same direction. A radio transmitter is then used to create a rotating magnetic field, and that causes the protons to wobble. This wobble then can be detected with another radio receiver. The real trick is to identify the location from which the protons are doing this emission, and that is done by varying the frequency of the radio wave, varying the magnetic field, and using other tricks.

As far as we know, MRI does no damage whatsoever to the body. The magnetic field and radio waves do not affect DNA, and there are no known side effects. The only problem with MRI imaging is that it costs a lot, since the magnet is expensive. Some people think the price will go down. Already some companies are offering relatively inexpensive MRIs, even as gifts that you can give to loved ones. It is not clear whether the MRI really is valuable as a way to scan healthy people for early signs of disease, or whether it will be used mostly to diagnose those with high likelihood of problems.

CAT scans (Computer-aided tomography scans)

Computer-aided tomography (CAT, sometimes just CT) is made by taking x-rays from many different directions. That's the "tomography" part. As with other x-rays, it is most sensitive to heavy elements such as calcium. A computer can then combine all these images to calculate a 3-D map of the x-ray absorption. That's the "computer-aided" part of the name. Once all the data are in the computer, then the medical doctor can display any portion of the data. In the image below, the computer plotted the data as it would look if a thin slice were taken through the head.



You'll notice that, even though x-rays are being used, the CT scan contains lots of detail about the brain. The reason is that in the regions that have no bone, the contrast can be enhanced, and show the very subtle difference in absorption that take place even in soft tissue.

The disadvantage of CAT scans (vs. MRI) is that it uses x-rays. Since many images must be taken, the dose can be large. CAT scans are often used in industry to look into structures to see if there are small cracks or other defects; in such cases, the dose is irrelevant.

PET scans (Positron-emission tomography)

Positrons are the antimatter of electrons. Certain isotopes emit positrons (instead of alpha or beta particles), and these isotopes are extremely useful in medicine. A list of some positron emitters is given below, along with the half lives:

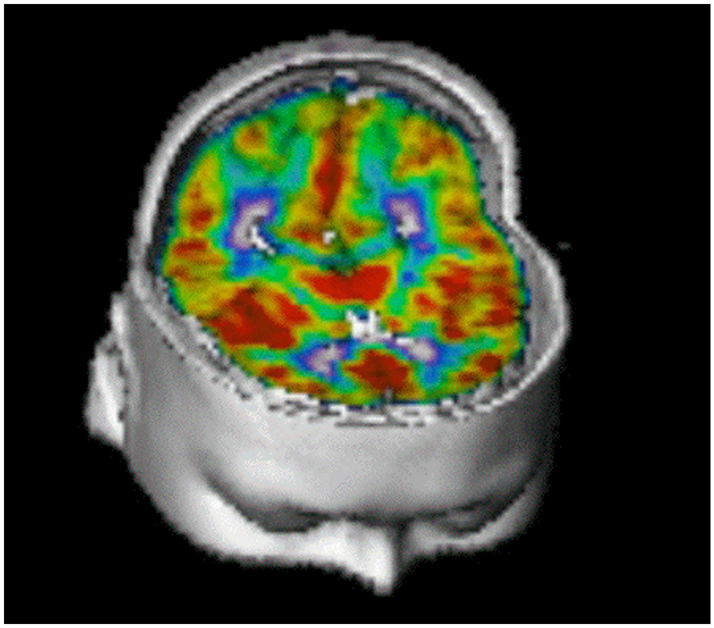
Carbon-11	20 minutes
Nitrogen-13	9 minutes
Oxygen-15	2 minutes
Fluorine-18	110 minutes
Iodine-124	4.2 days

To use PET, you prepare a material containing the positron emitter. For example, you could give the patient some iodine-124 (either in a pill, or injected into the blood). The iodine tends to concentrate at the thyroid gland of the patient. However, if part of the gland is not functioning right, that part may not get its share of iodine.

When iodine-124 emits a positron, the positron doesn't travel very far before it hits an electron. What that happens, the two particles disappear (that is called annihilation) and two gamma rays are emitted in exactly opposite directions. Those gamma rays leave the thyroid, and are detected with gamma detectors that measure exactly where they hit the detectors.

The instrument does not know where the gamma ray came from, but it knows that the origin was somewhere along the line connecting to two detection spots. To make an image requires millions of gamma rays. Each one gives the computer one line. The computer then calculates the distribution of I-124 in the thyroid that would give such a set of lines. That's the part called "tomography." Any region of the thyroid that is not functioning properly will have a blank spot. A part that is hyperactive will be bright.

Positron emitters such as carbon-11 can be incorporated in biological compounds, and then have their locations measured by PET scans. If you give the patient a oxygen-15, you can detect the most active parts of the brain by seeing where the oxygen flows. The figure below shows such a PET scan to monitor the activity in the brain. Different colors are generated by the computer to indicate the different intensities of signals coming from the various locations.



PET image

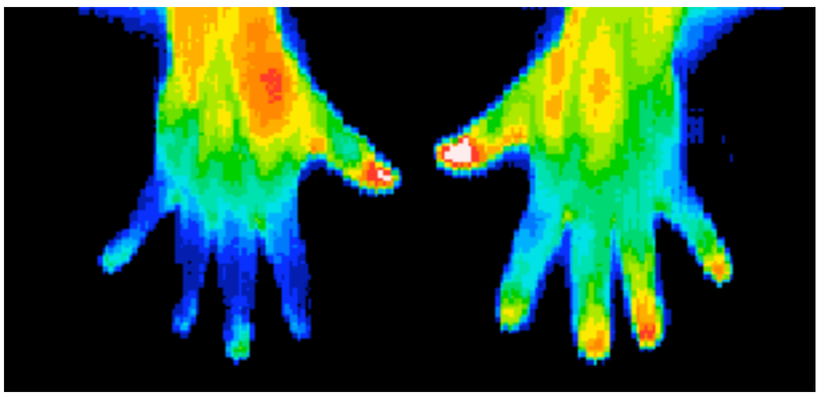
The short half life of the compounds used makes the method difficult to implement, since the radioisotopes decay so rapidly. But, on the other side, they do not last long within the body, so the rem dose to the patient is usually small.

Thermography

We discussed the fact that objects of different temperatures emit different wavelength of infrared radiation, and different intensities. A map of the IR emission therefore can give the medical doctor an image of the temperature of the skin. Thermography can also be done by painting the skin with a chemical (known as a "liquid crystal") whose visible color changes with temperature.

This is a relatively new technique, and it is not completely clear what its value will be. However it has already been found useful in diagnosing breast cancer, metabolic disorders, and certain kinds of injuries. The images below show some images taken for these situations.

Coronary Artery Disease (indicated by the oval) – and tooth infection
(from www.dititexas.com/page6.html)



Neuropathy in the fingers of the hand on the left
(from www.dititexas.com/page6.html)

Ultrasound – babies and bats

We have talked about imaging with many different kinds of waves. Why not use sound waves? The basic problem is that most sound waves have very long wavelength. A 1000 Hz sound wave, moving with v = 330 meters per second, has a wavelength is L = v/f = 33 cm. For medical imaging, the problem is even worse. Recall (Chapter 7) that the velocity of sound in water is 1482 m/sec, almost 1 mile per second. In body tissue, the velocity is about 1540 meters per second. A 1 kHz sound wave would have a wavelength of 1.5 meters.

But if we go to very high frequency sound, say 100 kHz, then the wavelength is $1540/10^5$ = 1.5 cm. These high frequency waves are called "ultrasound." Because of the way that the can shake small objects, they are used for cleaning jewelry and other small parts. Such devices are called "ultrasonic cleaners."

Medical ultrasound generators use a frequency of 1 to 1.5 MHz, with a wavelength of 1 mm. They are completely inaudible, but can be detected with sensitive microphones.

Such images are now commonly done to look at an unborn fetus. Ultrasound images can be used to detect possible problems long before birth. Below I show the image of the head of a baby, still in the womb, taken with ultrasound.

from www.obgyn.ufl.edu/ultrasound/MedinfoVersion/images/baby.gif

bats

Bats also use ultrasound to find prey and to avoid obstacles. Their ability to do this allows them to live in caves that are completely dark. Most bats can't see very well, and that leads to the expression "blind as a bat." But they don't need to. One flew into my living room recently, and zipped around the room like a trapped bird. But unlike birds, he crashed into nothing. In fact, I felt completely at ease watching him fly around, because I knew he wouldn't bump into me or anything else. Eventually he found the open door to the outside and he disappeared into the night.

Bat use frequencies just above the human audible range, about 20 kHz. In air, the wavelength is L = v/f = 330 meters/20000 Hz = 0.015 meters = 1.5 cm. That is good enough for them to locate flying insects[6], to skim just above the surface of water to take a drink, and to avoid physics professors in their homes.

Submarines use a similar system for detecting objects and other submarines underwater. Sonar is the underwater equivalent to radar. Sounds are emitted and their reflections mapped to determine the direction they are coming from. "Passive sonar" is more popular among submariners who don't want to be located by the sound they emit. Instead they listen to the sound that travels through the water (maybe in the sound channel) to detect noisy objects. The word sonar originated as an acronym for "SOund Navigation and Ranging.

[6] Bats could not "resolve" two close insects, but if they get a sonic reflection from a single bug, they can find the direction of the strongest signal; that gives them an accuracy far better than a wavelength.

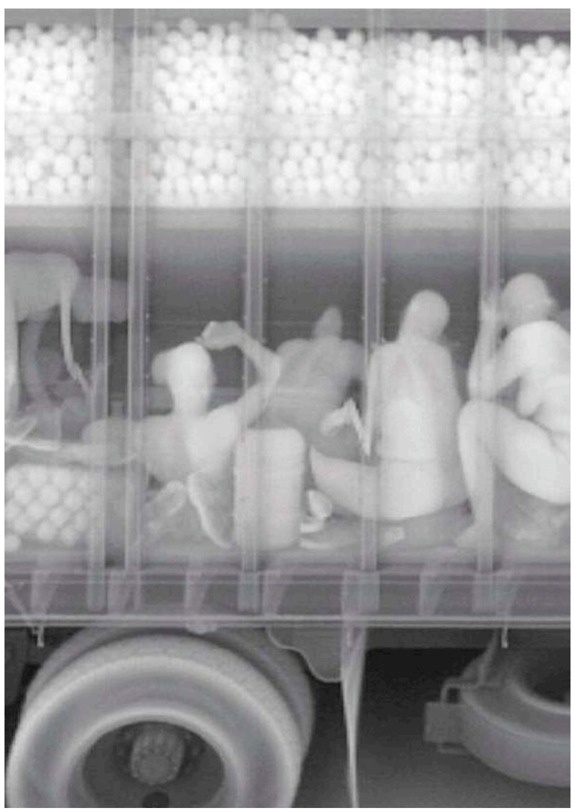
X-ray backscatter

X-rays are absorbed by heavy elements as they pass through matter. But some of them bounce backwards, mostly off electrons. This bouncing is called "Compton scattering" and the x-ray loses some energy (to the electron) when it does that.

The more electrons there are in the matter, the more backscatter there will be. Since there is one proton for every electron (and the number of neutrons is roughly equal to the number of protons), the result is that the density of electrons is approximately the same as the density of grams. So the amount of backscatter is roughly determined by the density of the material.

This backscatter has become important recently for some applications where you can't send the x-rays all the way through the object, or where you are more interested in seeing variations in density than in identifying the heavy elements (such as calcium in bone).

The image below shows an image taken from the side of a truck. Hidden in a compartment in the truck, under a layer of produce, are a group of illegal immigrants.



(Image from the American Science and Engineering Annual Report)

You can tell this is a backscatter image from the fact that you cannot see very far through the objects – the reflection is off the first few centimeters of material. Of course, some x-rays were also scattered backwards off the truck wall – but as long as that scattering was uniform everywhere, it is just a uniform grey across the image, and that was removed by increasing the contrast. You can also see the columns that hold up the wall.

X-ray backscatter can also be used to search a person for concealed weapons. There are several objections to this, however. Even though the radiation dose is extremely low, many people fear it anyway, and will refuse to be x-rayed. But even if they overcome this fear, some people object because of a privacy concern. The backscatter x-ray can easily penetrate light clothing, and return an image of the surface of the skin, giving an image of a person who appears to be naked.

END OF CHAPTER

Quick Review

All objects that are above absolute zero in temperature emit light. The temperature law is that the maximum wavelength emitted is L = 3000/T. At room temperature, the peak is in the infrared (L = 10 microns). At 3000 K, the color is red, at 5000 it gets white, and at 7000 it is blue. The total power radiation is proportional to the fourth power of the temperature, so that doubling the absolute temperature results in 16 times as much power radiated. Tungsten light bulbs emit reddish light because of their 2500 K temperature. "Heat lamps" emit primarily in the infrared. Humans emit very long wavelength infrared, but this can be imaged using special cameras. Infrared light emission can cool the ground and help form dew. Military special ops use infrared viewers to be able to see at night. Stinger missiles home in on the infrared signal emitted by engine exhaust. Mosquitoes and pit vipers use IR to detect enemies and prey.

Ultraviolet (UV) radiation is light with wavelength a bit shorter than that for visible light. "Black lights" emit UV. When UV hits a phosphor, the phosphor absorbs the UV, and emits visible. Such phosphors can make a material glow, and even look whiter than white. UV can cause sun tan, sunburn, and skin cancer. It is also responsible for windburn. Most modern sunglasses block UV to prevent the eyes from damage. When UV from the Sun enters the atmosphere, it creates an ozone layer at an altitude of about 50,000 feet. The ozone is a strong UV absorber, and it keeps intense UV from reaching the ground. The ozone can be destroyed by chemicals known as chloro-fluorocarbons, or CFCs, which were extensively used in refrigerators, air conditioners, aerosol sprays, and for cleaning, until they were outlawed.

The earth is warmed by visible light, and cools by IR emission. It is even warmer because of the greenhouse effect: the atmosphere absorbs IR, and prevents the Earth from cooling as much as it otherwise would. Greenhouse absorbers include water vapor, carbon dioxide, and ozone. Humans have been adding carbon dioxide to the atmosphere, and this may be responsible for the observed global warming. A similar process makes the interior of automobiles get hot when they sit in the sun.

Invisible light includes radio waves, TV and FM waves, microwaves, x-rays and gamma rays. They are distinguished by their different frequencies and wavelengths. For all of them, however, f L = c, where c is the speed of light. Microwaves are used to heat water, and for radar. They can damage eyes if they cause the interior to heat. X-rays and gamma rays have many applications for medical imaging, including Computer-aided tomography (CAT) scans. Magnetic Resonance Imaging (MRI) was once called Nuclear Magnetic Resonance. It gives good images of soft tissue containing hydrogen. Positron emission tomography can show where chemicals (such as iodine) go in the body. Positrons emit gamma rays, in opposite directions, when they annihilate with electrons.

Infrared radiation can be used to image the temperature of the skin, and that is useful for detecting breast cancer and other physical problems. Ultrasound can also be used to image within the body, for example, to give images of a baby in the fetus. Bats use ultrasound to detect insects and obstacles. They bounce high frequency sound off objects, and detect the bounce. When submarines use the same principle, we call it sonar.

X-ray backscatter is useful for looking into the surface of an object that is too thick to penetrate with x-rays.

Discussion topics

Patients dying of cancer have refused to be diagnosed with "Nuclear Magnetic Resonance Imaging" because of their fear of radioactivity. What were the real risks and benefits? What does this say about the feeling of people about "nukes"?

There is uncertainty about many possible effects in greenhouse warming. Given that, what action do you think is appropriate? Is there any downside, if the warming turns out to be natural? Try to evaluate the risks and benefits of public policy.

Essay questions

Discuss the ways in which invisible light can be used to help medical diagnosis. What other kinds of waves can also be used?

Humans have been polluting the atmosphere in ways that could have lasting effects for future generations. What are the chemicals that have been put into the air that could do this? What effects could they have? Describe as much of the relevant physics as you can.

Describe the dangers and benefits of ultraviolet radiation. How can it cause harm, and how can it be used for business, and how can it be used for beneficial purposes?

Discuss the military applications of infrared light.

Short questions

Which animals can detect and use UV radiation? Mark all that can. (Caution: possibly a trick question.)

( ) pit vipers
( ) cats
( ) mosquitoes
( ) none of the above

Ultrasound is used by (check all that apply):

( ) pregnant mothers
( ) bats
( ) jewelers
( ) stinger missiles

"Whiter than white"

( ) is a meaningless slogan
( ) means there is more white present than could be reflected
( ) depends on IR radiation
( ) is a result of x-ray imaging

Microwave ovens tend to warm

( ) carbon dioxide
( ) calcium
( ) oxygen
( ) water

Which of the following has the shortest wavelength?

( ) microwaves
( ) radio waves
( ) ultrasound
( ) TV signals

Windburn comes from

( ) the wind
( ) UV
( ) IR
( ) visible light

If you double the temperature of a tungsten filament, the energy emitted

( ) doubles
( ) stays the same
( ) goes up 4 times
( ) goes up 16 times

Thyroid activity is best detected with

( ) CAT scan
( ) MRI
( ) PET scan
( ) thermography

Bones are observed best with

( ) CAT scan
( ) MRI
( ) PET scan
( ) thermography

Radar uses

( ) sound waves
( ) microwaves
( ) gamma rays
( ) visible light

We fear future global warming will be caused by

( ) CFCs
( ) carbon dioxide
( ) ozone emissions
( ) radar

Ozone protects us from

( ) smog
( ) IR radiation
( ) sunburn
( ) carbon dioxide

UV can be used to

( ) prevent cancer
( ) reduce global warming
( ) kill bacteria
( ) detect mosquitoes